Silicon Detectors for the LHC Phase-II Upgrade and Beyond

RD50 Status Report

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CERN RD50 INFN Istituto Nazionale di Fisica Nucleare

CTD/WIT 2019
Connecting the Dots and Workshop on Intelligent Trackers

IFIC, València, Spain
2nd - 5th April 2019

Presentation Outline

A. The RD50 Collaboration

B. State-of-the-art Silicon Detectors for High-Energy Particle Tracking
   1. Radiation Damage and Defects Characterization
   2. Detectors Characterization
   3. Novel Structures and Technologies

C. Radiation Tolerance also Beyond HL-LHC

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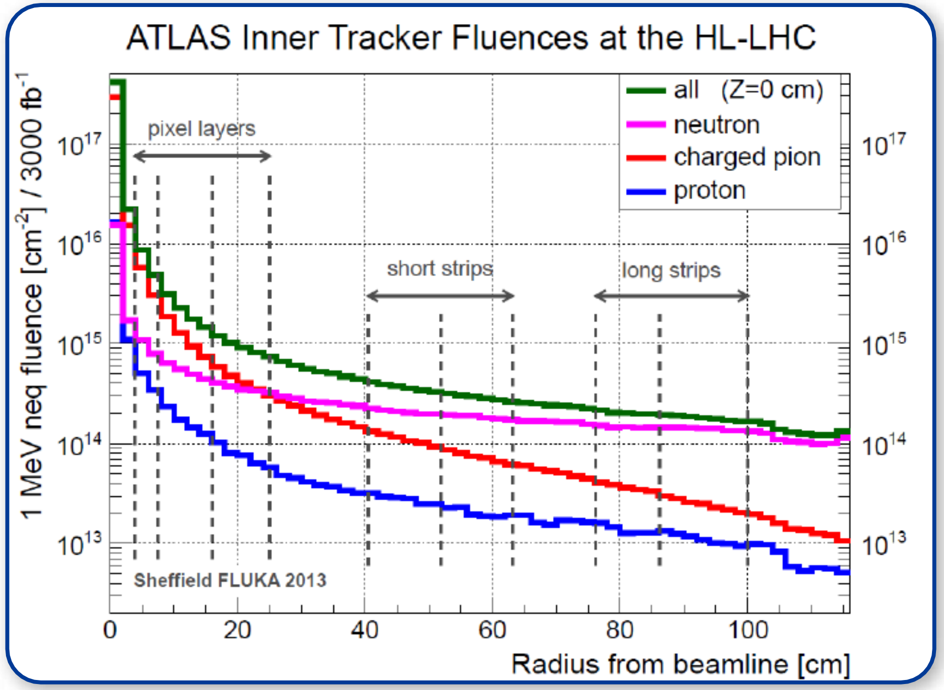
A. The RD50 Collaboration

RD50 Motivation

LHC Upgrade towards High-Luminosity LHC (HL-LHC): ~4000 fb^{-1} (×6)



I. Dawson, P. S. Miyagawa, *ATLAS Upgrade radiation background simulations*

- Expected *equivalent fluence*: > $2{\cdot}10^{16}$ n_{eq}/cm^2 (or > $7{\cdot}10^{17}$ n_{eq}/cm^2, 200 MGy, in FCC)
- Current LHC detectors unable to operate within such radiation environment

⇩

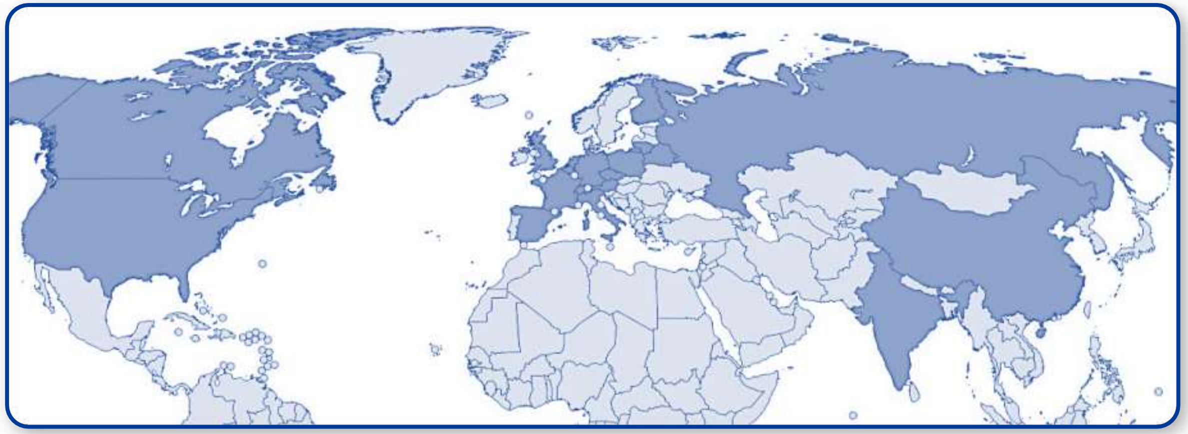
RD50: mandate to develop and characterize radiation-hard silicon sensors for future colliders

A. The RD50 Collaboration

RD50: 63 institutes and more than 300 members (see http://cern.ch/rd50)

52 European institutes

Austria (Wien), Belarus (Minsk), Belgium (Louvain), Croatia (Zagreb), Czech Republic (Prague (3x)), Finland (Helsinki, Lappeenranta), France (Paris, Marseille, Orsay), Germany (Bonn, Göttingen, Dortmund, Erfurt, Freiburg, Hamburg (2x), Karlsruhe, Munich (2x)), Greece (Athens), Italy (Bari, Perugia, Pisa, Trento, Torino), Lithuania (Vilnius), Netherlands (NIKHEF), Poland (Kraków, Warsaw (2x)), Romania (Bucharest (2x)), Russia (Moscow, St. Petersburg), Slovenia (Ljubljana), Spain (Barcelona (3x), Santander, **València**), Switzerland (CERN, PSI), United Kingdom (Birmingham, Glasgow, Lancaster, Liverpool, Manchester, Oxford, RAL)



8 North-America institutes

USA (Berkeley, BNL, Brown Uni, Fermilab, New Mexico, Santa Cruz, Syracuse), Canada (Montreal)

1 Middle-East institute

Israel (Tel Aviv)

2 Asian institutes

India (Delhi), China (Beijing)

A. The RD50 Collaboration

Co-Spokespersons

Gianluigi Casse (**Liverpool Uni.**, **UK** and **FBK-CMM**, **Trento**, **Italy**) & *Michael Moll* (**CERN EP-DT**)

Defect / Material Characterization	**Detector Characterization**	**New Structures**	**Full Detector Systems**
Ioana Pintilie (NIMP Bucharest)	*Eckhart Fretwurst* (Hamburg University)	*Giulio Pellegrini* (CNM Barcelona)	*Gregor Kramberger* (Ljubljana University)

Defect / Material Characterization
- Characterization of microscopic properties of standard, defect engineered and new materials, pre- and post-irradiation
- DLTS, TSC, …
- SIMS, SR, …
- NIEL (calculations)
- Cluster and Point defects
- Boron related defects

Detector Characterization
- Characterization of test structures: *I*(*V*), *C*(*V*), CCE, TCT, …
- Development and testing of defect engineered silicon devices
- EPI, MCZ and other materials
- NIEL (experimental)
- Device modeling
- Operational conditions
- Common irradiations

- Wafer procurement (M. Moll)
- Acceptor removal (G. Kramberger)
- TCAD simulations (J. Schwandt)

New Structures
- 3D detectors
- Thin detectors
- Cost effective solutions
- Other new structures
- Detectors with internal gain
- LGAD: Low-Gain Avalanche Detectors
- Deep depleted Avalanche Detectors
- Slim Edges
- HV-CMOS

- LGAD (S. Hidalgo)
- HV-CMOS (E. Vilella)
- Slim Edges (V. Fadeyev)

Full Detector Systems
- LHC-like tests
- Links to HEP (LHC upgrade, FCC)
- Links electronics R&D
- Low ρ strips
- Sensor readout (Alibava)
- Comparison:
  - pad-mini-full detectors
  - different producers
- Radiation Damage in HEP detectors
- Timing detectors
- Test beams (M. Bomben & G. Casse)

Collaboration Board Chair & Deputy: *G. Kramberger* (Ljubljana) & *J. Vaitkus* (Vilnius), Conference committee: *U. Parzefall* (Freiburg)
CERN contact: *M. Moll* (EP-DT), Secretary: *V. Wedlake* (EP-DT), Budget holder & GLIMOS: *M. Moll* & *M. Glaser* (EP-DT)

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B. State-of-the-art Silicon Detectors for High-Energy Particle Tracking
   1. Radiation Damage and Defects Characterization
   2. Detectors Characterization
   3. Novel Structures and Technologies

C. Radiation Tolerance also Beyond HL-LHC

B. State-of-the-art Si Detectors for HE Tracking

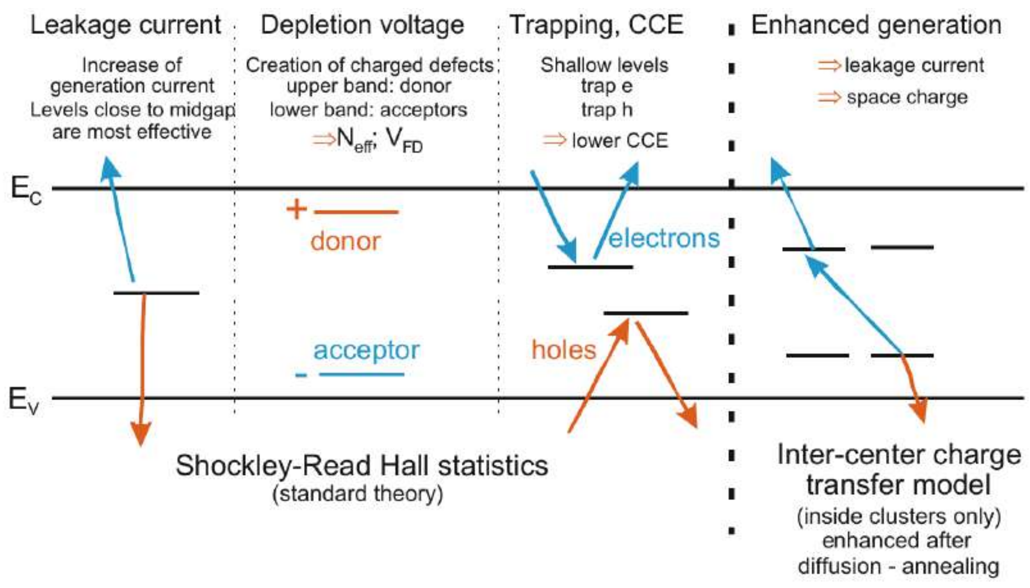
Summary of main RD50 achievements (2002-2019)

- Development of the *p*-type Silicon strip and pixel technology as well as LGAD (Low-Gain Avalanche Diodes), double column 3D detectors, and demonstration of the performance of planar segmented sensors to the maximum fluences anticipated for the HL-LHC ($3 \cdot 10^{16}$ n_{eq}/cm^2)
- Extensive evaluation of defect engineered Silicon (and other semiconductor materials) and characterization: identification of defects responsible for the degradation of various detectors figures-of-merit defining the state-of-the-art in the corresponding solid-state community
- Development of several unique characterization methods and systems for sensor and material analyses: Transient Current Technique (TCT), edge-TCT, Two-Photon Absorption-TCT (TPA-TCT), ALiBaVa readout system, standardized measurement and analyses procedures (partly now marketed through spin-off companies)
- Data collection and development of damage parameters/models essential for sensor design (TCAD input data) and for planning the scenarios of future HEP experiments and their upgrades (evolution of leakage current, CCE, power consumption, noise, …)
- Close links to the current LHC experiments and their upgrades

B. State-of-the-art Si Detectors for HE Tracking

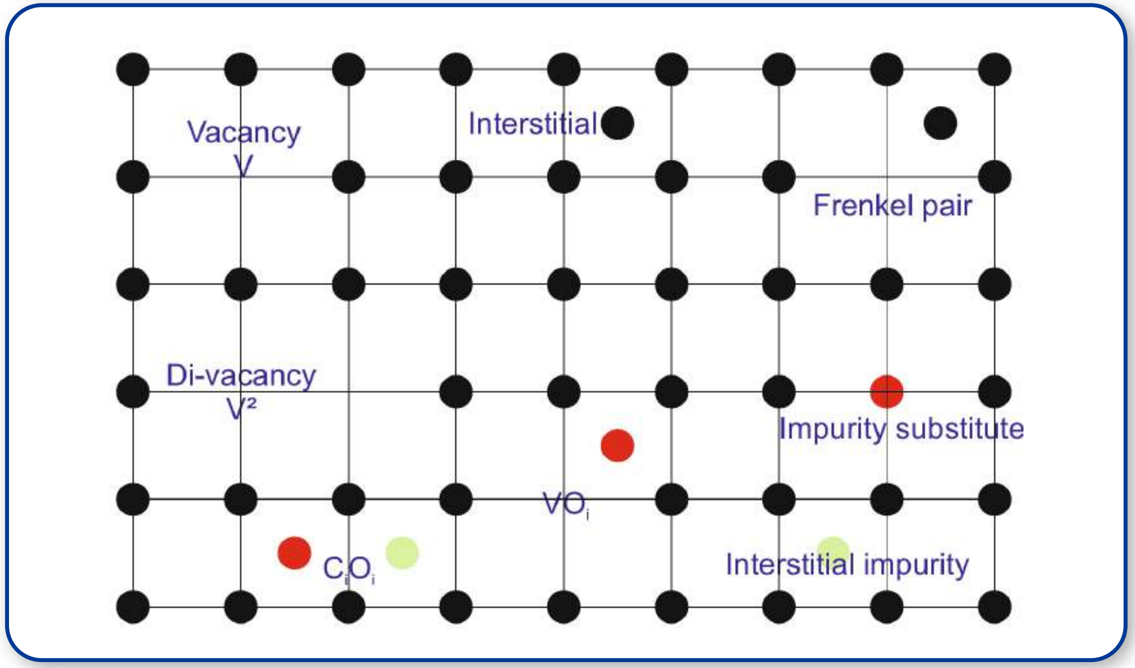
1. Radiation Damage and Defects Characterization

- Identify defects responsible for trapping, leakage current, change of CCE, N_{eff} or electric field
- Understand if this knowledge can be used to mitigate radiation damage (e.g. defect engineering)
- Deliver input for device simulations to predict detector performance under various conditions
- Huge amount of samples irradiated with protons, neutrons, electrons, ^{60}Co-γ



B. State-of-the-art Si Detectors for HE Tracking

1. Radiation Damage and Defects Characterization

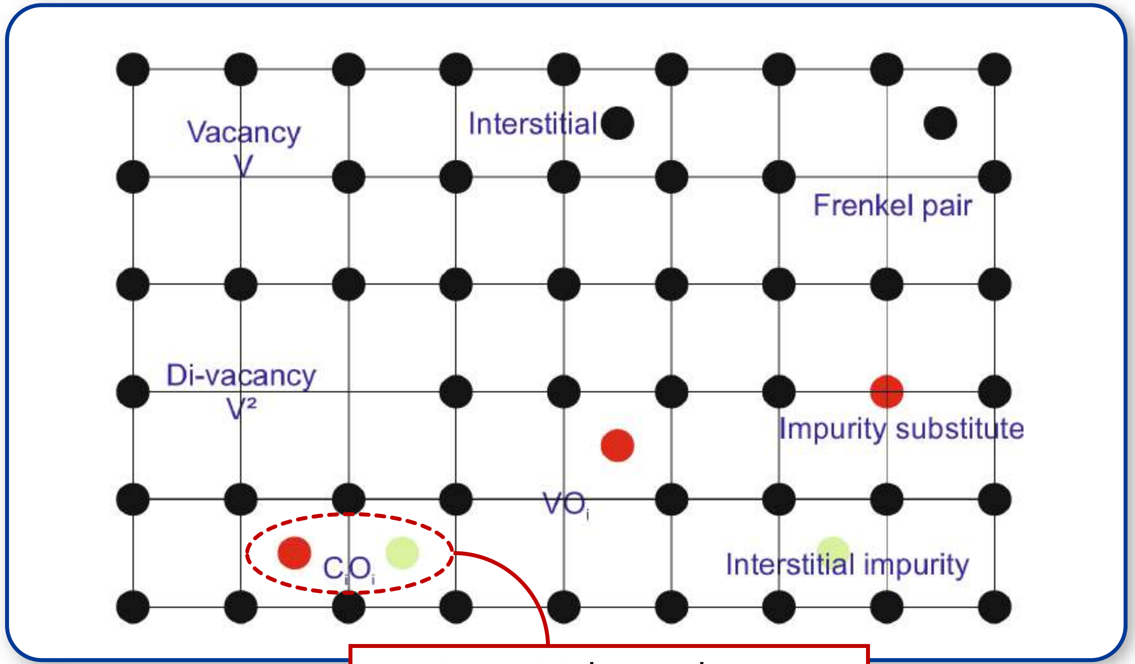


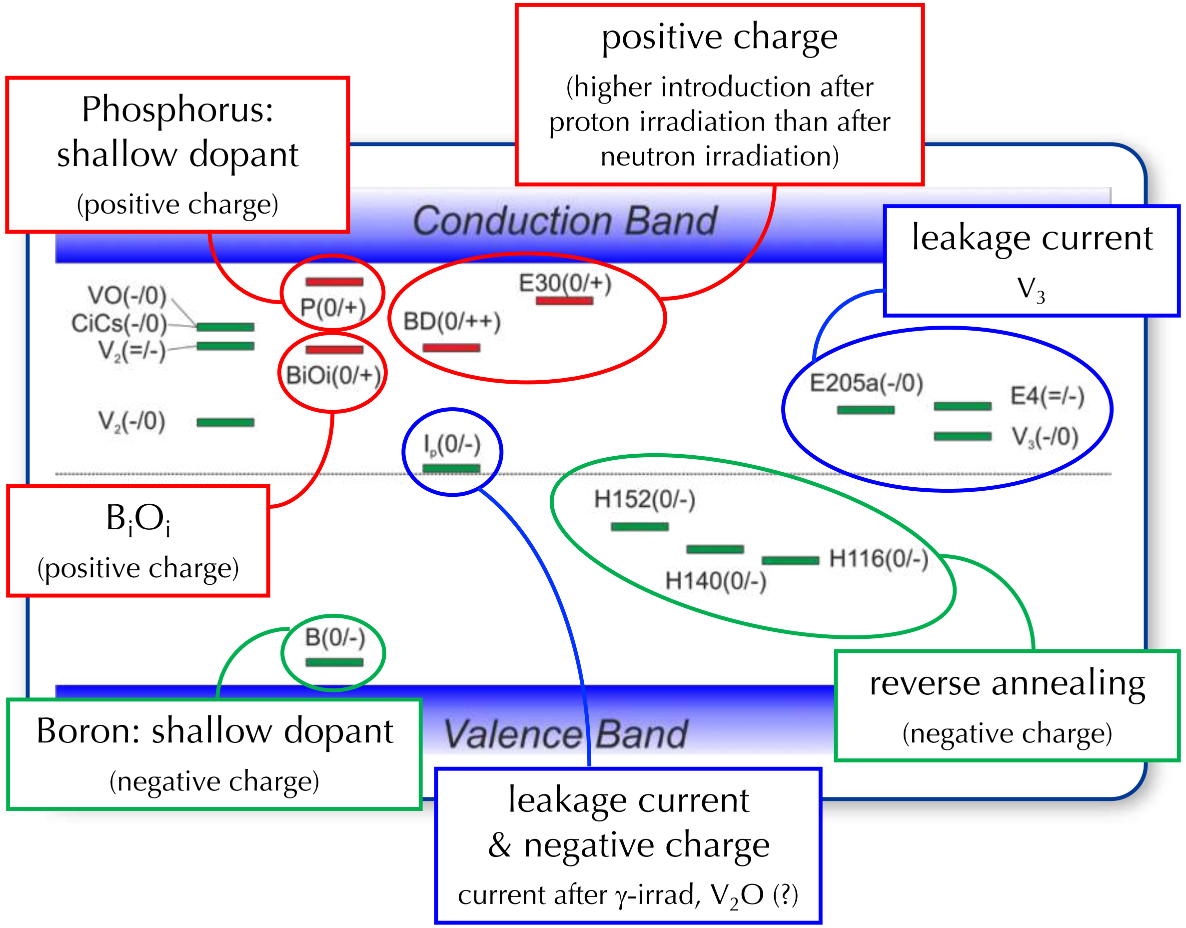
Significant progresses in characterizing defects through specific analysis performed with various tools inside RD50:

- c-DLTS (capacitance-Deep-Level Transient Spectroscopy)
- TSC (Thermally Stimulated Currents)
- PITS (Photo Induced Transient Spectroscopy)
- FTIR (Fourier Transform Infrared Spectroscopy)
- EPR (Electron Paramagnetic Resonance)
- TCT (Transient Current Technique)
- CV/IV (Capacitance/Current-Voltage Measurement)
- MW-PC (Microwave Probed Photo Conductivity)
- PC, RL, i-DLTS, TEM, … and TCAD simulations

1. Radiation Damage and Defects Characterization

The map of identified defects



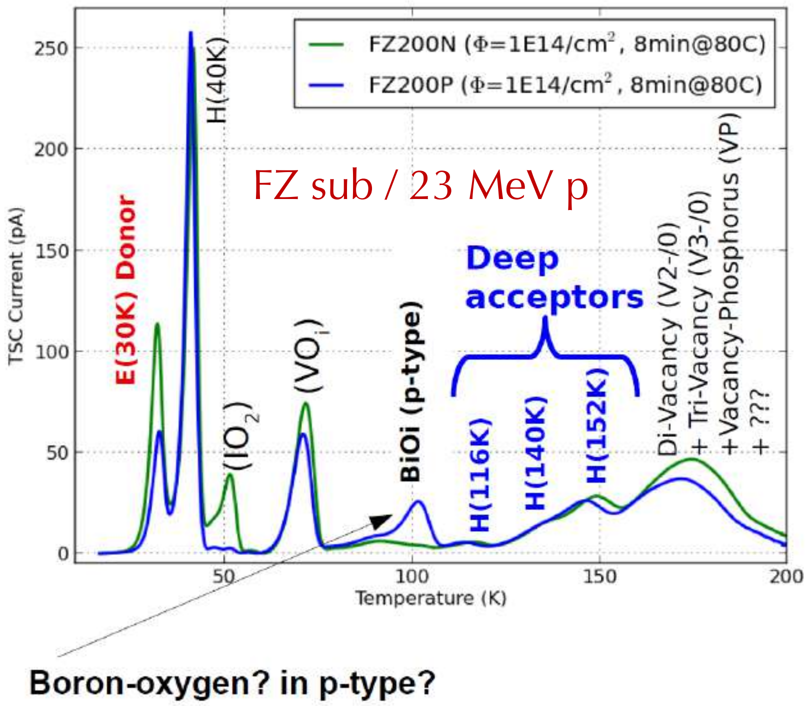


B. State-of-the-art Si Detectors for HE Tracking

1. Radiation Damage and Defects Characterization

Micro- & macro-scopic study

TSC – Thermally Stimulated Current



E. Donegani *et al.*, RD50 workshop, Dec 2015

Deep acceptors, e.g. H(116K), and shallow donors (E30K) alter space charge

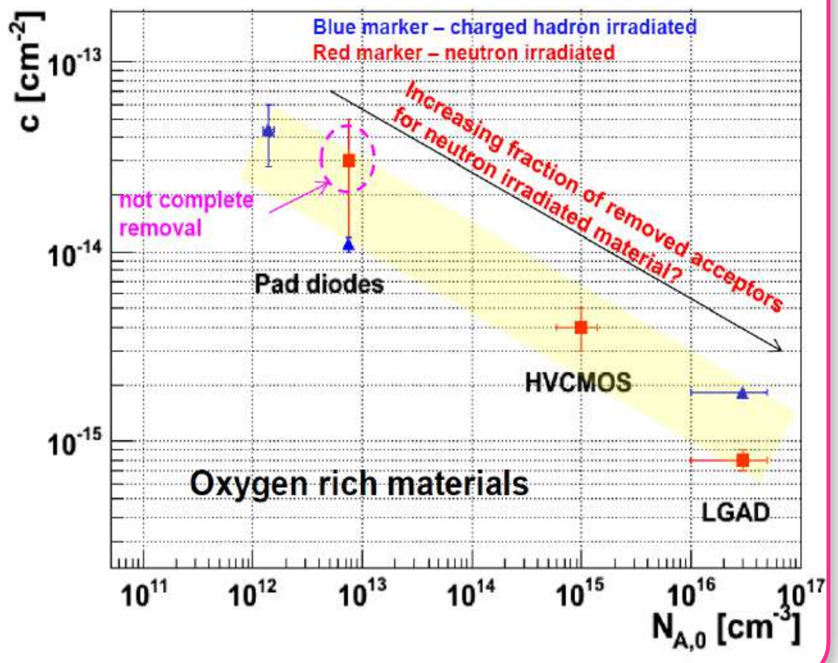
Some defect only seen in *p*-type (Boron containing) materials; indication for "Boron removal" (de-activation) by defect kinetics (e.g. $B_i \rightarrow B_iO_i$)

So-called "acceptor removal" responsible for:

- Gain degradation in sensors with intrinsic gain
- Good performance of low resistivity CMOS sensors after high irradiation
- Not studied before, being the focus on *n*-type Silicon

Acceptor de-activation (empirical) law

$$N_A(\phi) \approx N_A(0) \cdot \exp[-c \cdot \phi]$$



G. Kramberger *et al.*, RD50 workshop, June 2015

B. State-of-the-art Si Detectors for HE Tracking

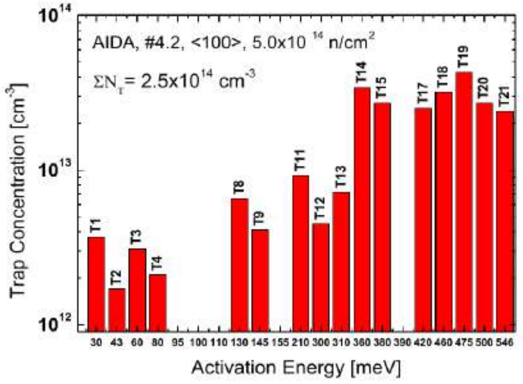
1. Radiation Damage and Defects Characterization

Examples of ongoing activities: **NitroStrip** project

Nitrogen-enriched *n*-type FZ wafers after irradiation ($5 \cdot 10^{14}$ n_{eq} /cm^2) showing lower trap density with the increasing of N concentration

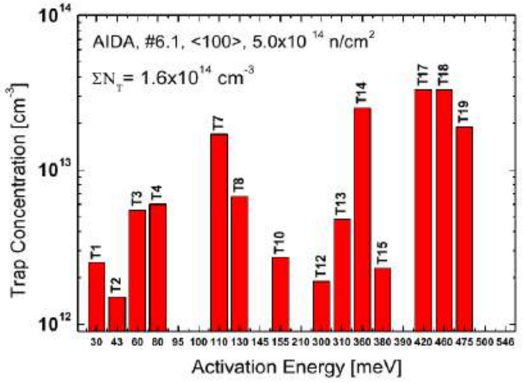
Kaminski, RD50 workshop, Nov 2014

$[N] = 1.42 \cdot 10^{15}$ cm^{-3}



$[traps] = 2.5 \cdot 10^{14}$ cm^{-3}

$[N] = 2.0 \cdot 10^{15}$ cm^{-3}

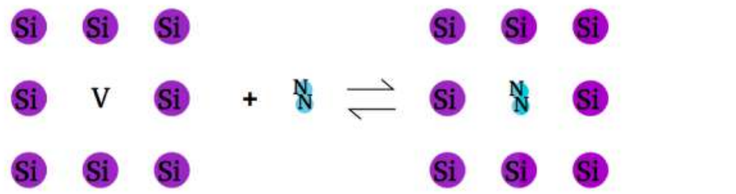


$[traps] = 1.6 \cdot 10^{14}$ cm^{-3}

W. von Ammon *et al.*, J. Cryst. Growth 226, 19 (2001)

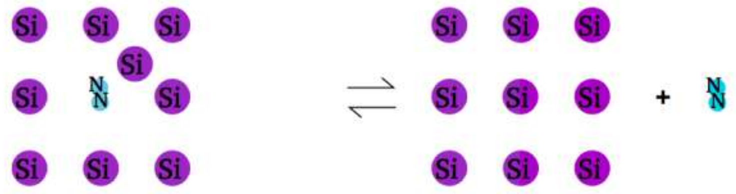
Vacancy Suppression

$$N_2 + V \rightleftharpoons N_2V$$



Interstitial Suppression

$$N_2V + I \rightleftharpoons N_2$$

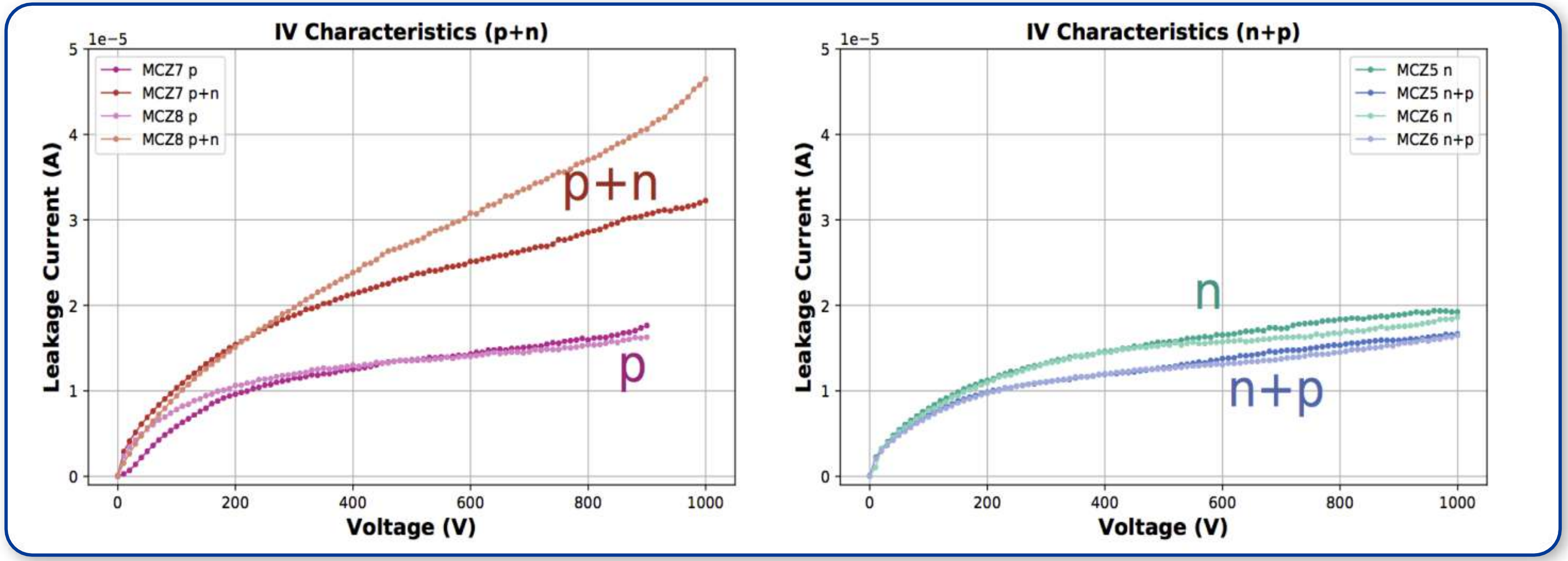


Similar effects may also occur with Carbon implantation (Watkins mechanism)

1. Radiation Damage and Defects Characterization

Examples of ongoing activities: **mixed irradiations**

MCZ *n*-type samples irradiated with 23 MeV protons at KIT ($3 \cdot 10^{14}$ n_{eq}/cm^2) and neutrons in Ljubljana ($3 \cdot 10^{14}$ n_{eq}/cm^2). Total fluence: $6 \cdot 10^{14}$ n_{eq}/cm^2



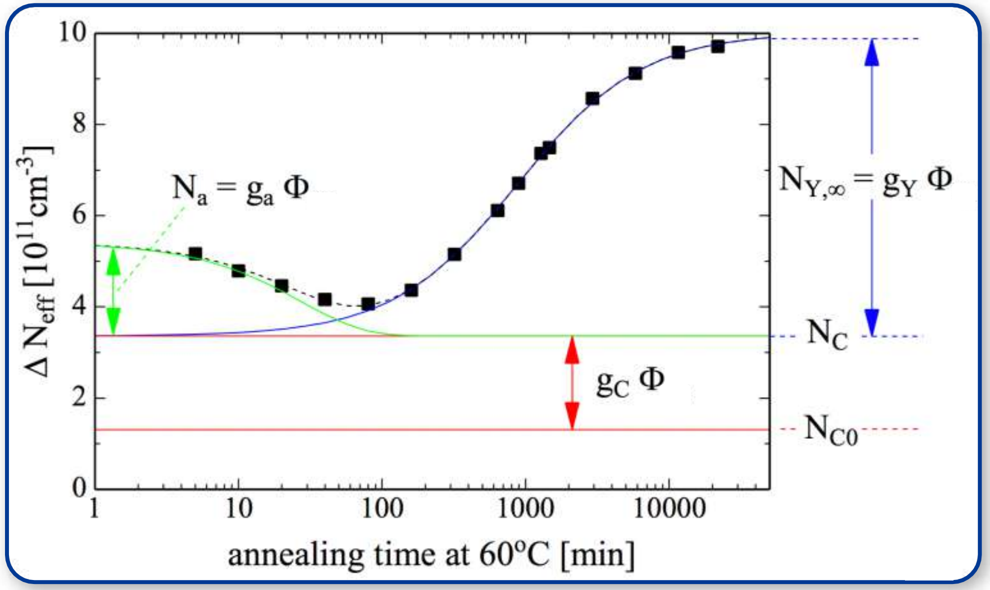
Gosewisch 33rd RD50 workshop, Nov 2018

B. State-of-the-art Si Detectors for HE Tracking

1. Radiation Damage and Defects Characterization

Damage parametrization: **the Hamburg Model**

$$\Delta N_{eff}(\phi,t) = N_{eff}(0) - N_{eff}(\phi,t)$$
$$= N_a(\phi,t) + N_C(\phi) + N_Y(\phi,t)$$



a) Short-term annealing:

$N_a(\phi,t) = \phi \cdot \sum [g_{a,i} \cdot \exp(-t/\tau_i)]$

First-order decay of acceptors, proportional to the fluence ϕ

b) Stable damage:

$N_C(\phi) = N_{C,0} \cdot [1 - \exp(-c \cdot \phi)] + g_C \cdot \phi$

Donor de-activation & introduction of stable acceptor-like defects

c) Long-term reverse annealing:

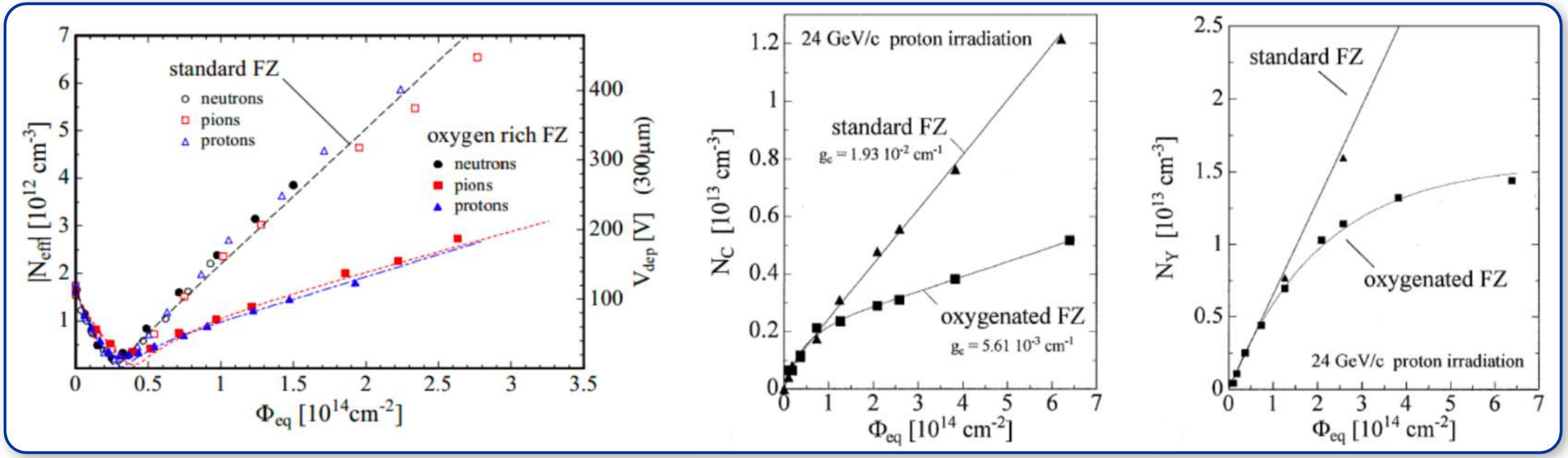
$N_Y(\phi,t) = N_{Y,\infty}(\phi) \cdot \{1 - [\ 1 / ((1+t) / \tau\ )\ ]\}$

Second-order parametrization, independent of fluence ϕ

B. State-of-the-art Si Detectors for HE Tracking

1. Radiation Damage and Defects Characterization

Damage parametrization: **the Hamburg Model**



G. Lindström, LEB-workshop, Sep 2000 & G. Lindström, NIM-A (**466**)2, 308–326, 2001

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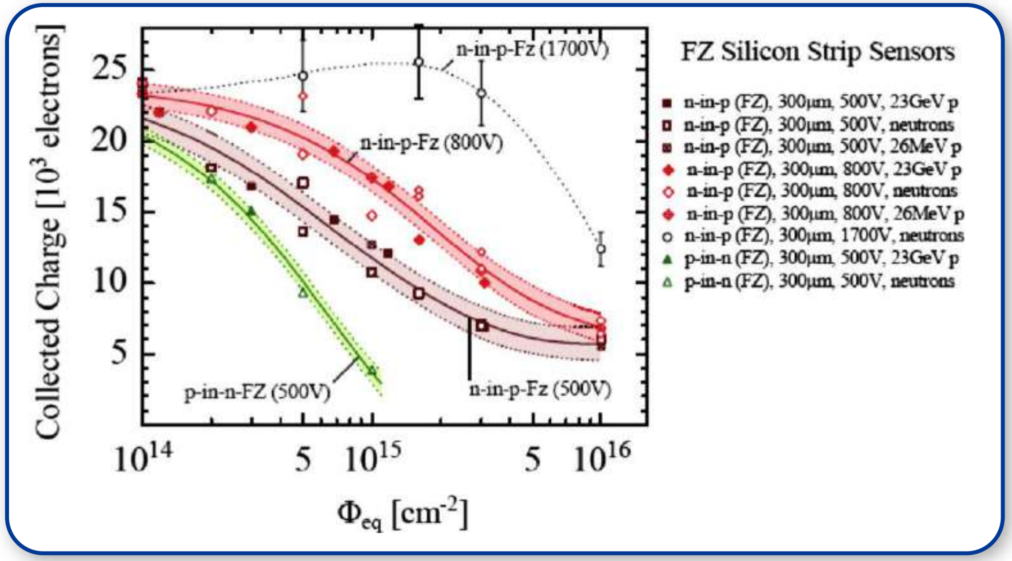
B. State-of-the-art Si Detectors for HE Tracking

2. Detectors Characterization

- The irradiation introduces defects which act as trapping center for the charge generated by an ionizing particle
- This reduce the overall signal, thus, affects the detector efficiency
- When the effective trapping time becomes of the order of the *electron/hole drift time* (~5-20 ns) the charge integrated at the electrodes by the front-end electronics is reduced

$$Q_{e,h}(t) = Q^0_{e,h} \cdot \exp\left(-\frac{t}{\tau_{\text{eff } e,h}}\right)$$

$$\frac{1}{\tau_{\text{eff } e,h}} = \beta_{e,h}(T,t) \cdot \phi \propto N_{\text{traps}}$$

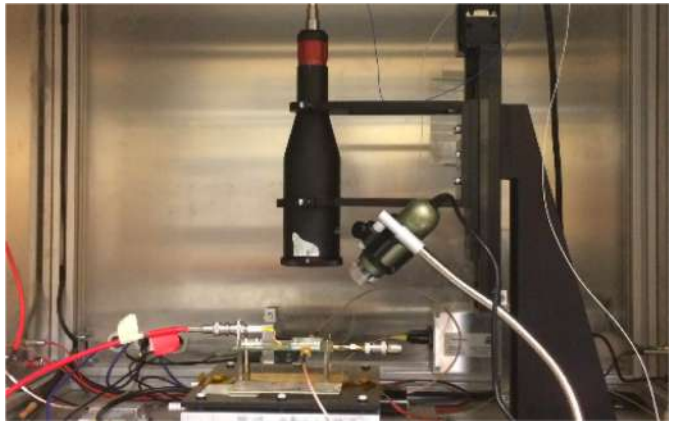


M. Moll, 2009

2. Detectors Characterization

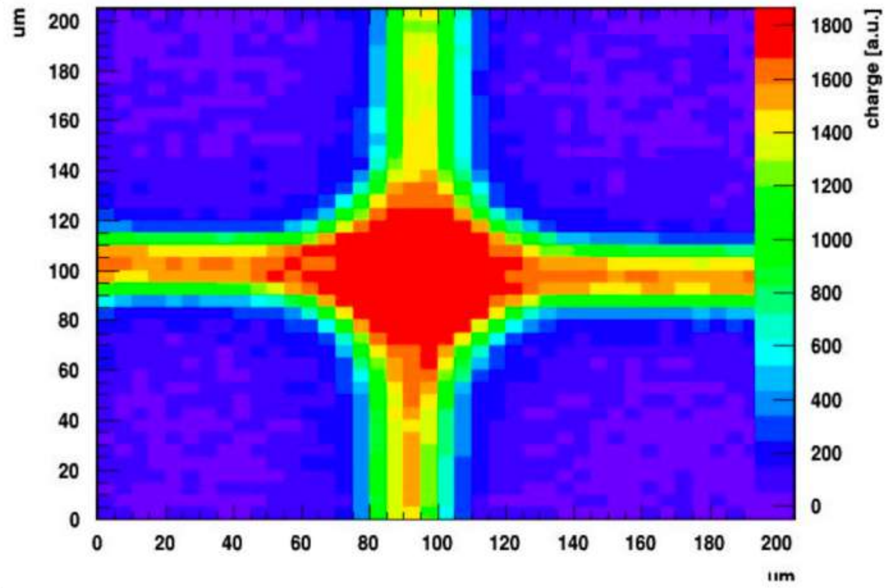
Besides static analysis, with *I*(*V*) and *C*(*V*) curves, RD50 also provides detailed characterizations about the device internal properties

- 2D map of active areas



TCT (Transient Current Technique)

F. Siviero *et al.*, RD50 workshop, Nov 2018



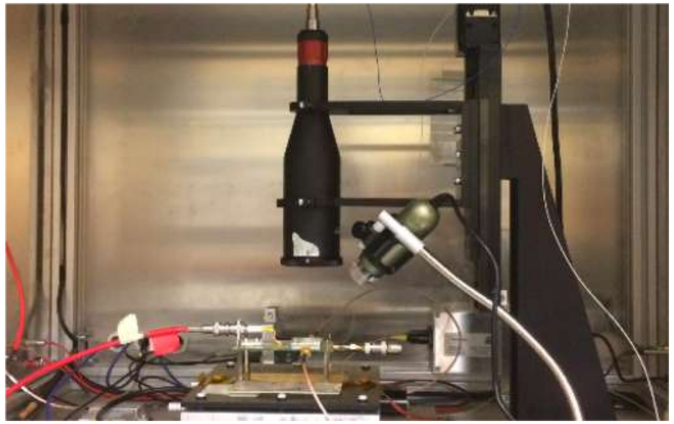
2×2 CMS pad-array: UFSD3-run by FBK

B. State-of-the-art Si Detectors for HE Tracking

2. Detectors Characterization

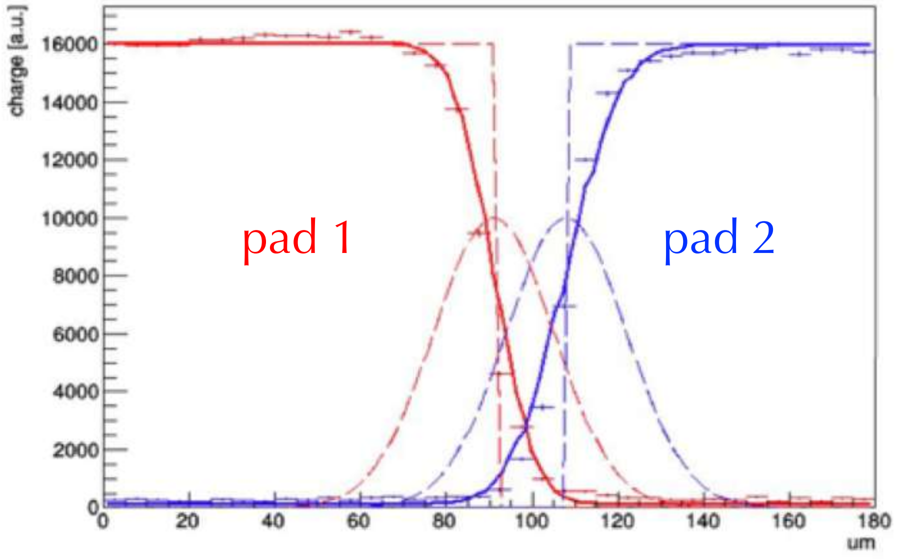
Besides static analysis, with *I*(*V*) and *C*(*V*) curves, RD50 also provides detailed characterizations about the device internal properties

- 2D map of active areas
- Inter-pad distance (*fill-factor* studies)



TCT (Transient Current Technique)

F. Siviero *et al.*, RD50 workshop, Nov 2018



2×2 CMS pad-array: UFSD3-run by FBK

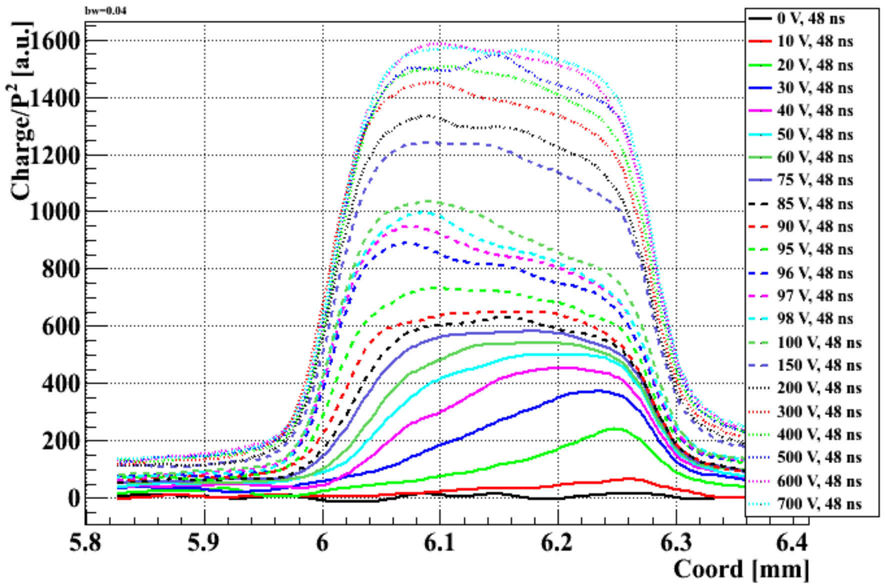
B. State-of-the-art Si Detectors for HE Tracking

2. Detectors Characterization

Besides static analysis, with *I*(*V*) and *C*(*V*) curves, RD50 also provides detailed characterizations about the device internal properties

- Collected charges as a function of depth

front-TPA (Two-Photon Absorption)



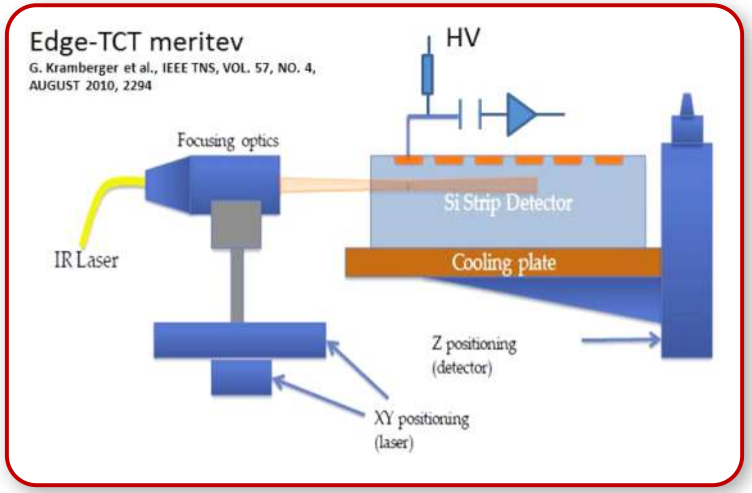
G. Casse, VERTEX, Oct 2018

B. State-of-the-art Si Detectors for HE Tracking

2. Detectors Characterization

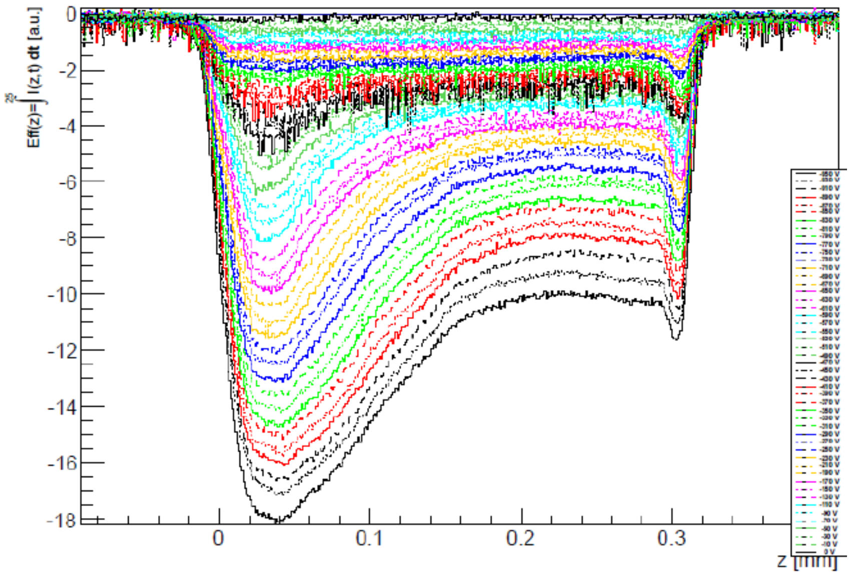
Besides static analysis, with *I*(*V*) and *C*(*V*) curves, RD50 also provides detailed characterizations about the device internal properties

- Collected charges as a function of depth
- Electric field as a function of depth



edge-TCT

M. Fernandez, S. Wonsak, PSD10, 2014



B. State-of-the-art Si Detectors for HE Tracking

2. Detectors Characterization

Devices characterization does not mean only laboratory measurements. RD50 Collaboration has a simulation group dedicated to the process/detectors modeling with:

- commercial TCAD tools: *Synopsis Sentaurus, Sylvaco Atlas*
- in-house developed software: *KDetSim, TRACS, Weightfield2*
- radiation simulators: *Geant, Fluka, Pythia*

Simulations allow comparisons with experimental data and, thus, the calibration of physical models and their parameters. Moreover, such calibration lead to device design, development and optimization through the modeling of:

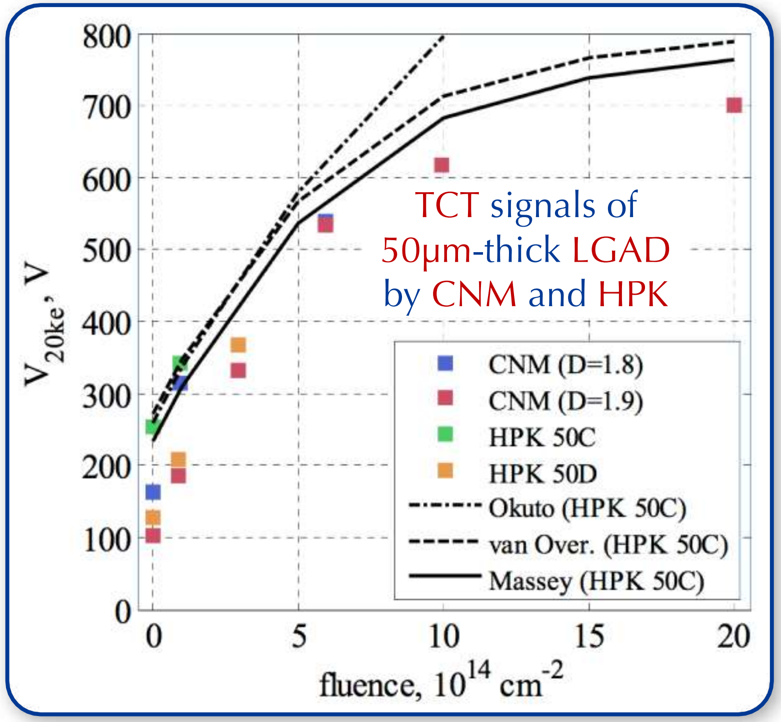
- electrical behavior: $I(V,T)$ and $C(V,T)$ curves, breakdown, depletion voltage, …
- electric field / mobility simulations
- charge generation (and/or multiplication)
- radiation damage effects: surface / bulk defects production, trapping, acceptor de-activation, …

B. State-of-the-art Si Detectors for HE Tracking

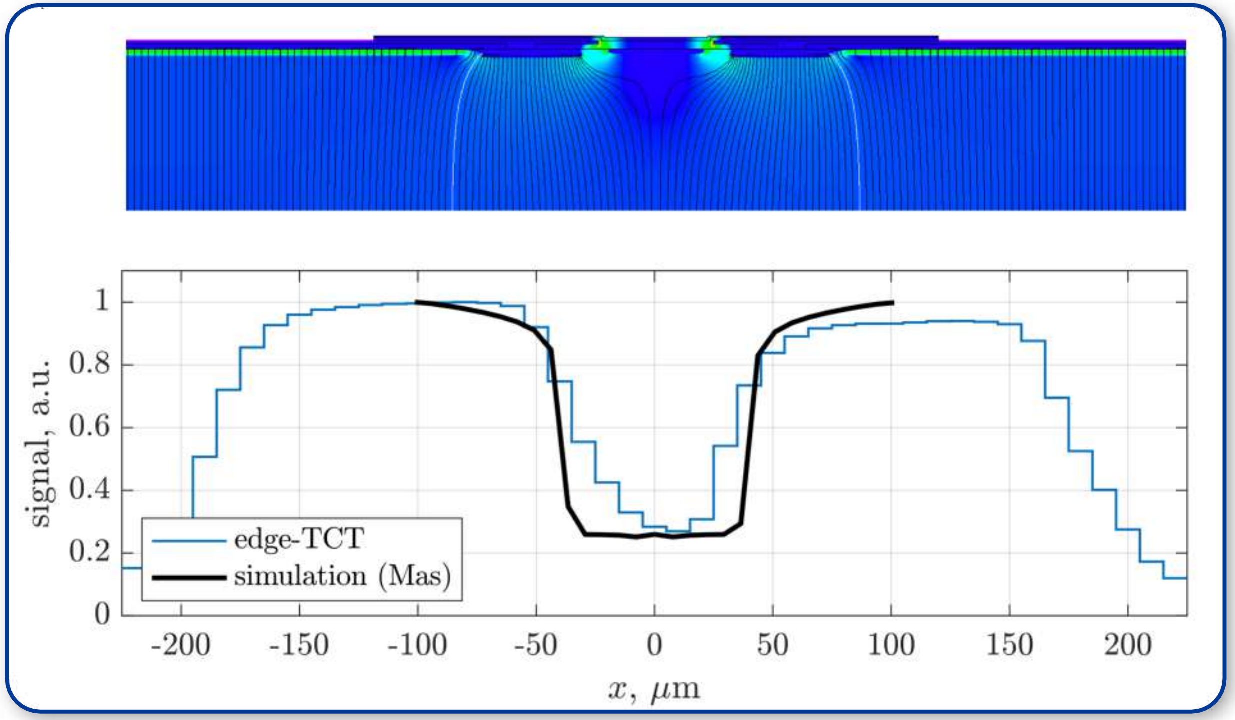
2. Detectors Characterization

2D or 3D TCAD (Technology Computer-Aided Design) simulations

M. Mandurrino, RD50 workshop, Jun 2017



M. Mandurrino, RD50 workshop, Nov 2017



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B. State-of-the-art Si Detectors for HE Tracking

3. Novel Structures and Technologies

Developed RD50 Structures:

- planar technology: pixel / strip detectors (sensors without gain), LGAD (Low-Gain Avalanche Diode)
- 3D technology
- towards monolithic implementation: HV-CMOS
- full-detector systems

R&D and Optimization:

- radiation hardness: mitigate acceptor de-activation with Gallium and Carbon implantation
- timing performances and 4D tracking
- fill-factor: new inter-pad terminations (LGAD with trenches) and AC-coupled readout

B. State-of-the-art Si Detectors for HE Tracking

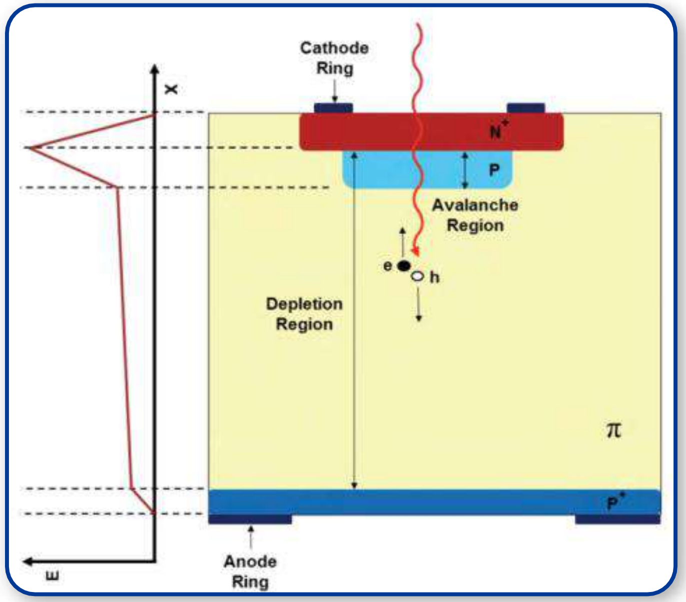
3. Novel Structures and Technologies

LGAD

- Three foundries: CNM (Barcelona, ES), FBK (Trento, IT) and HPK (Japan)
- Several designing/testing institutes involved: TIFPA (Trento, IT), INFN (Torino, IT), CERN (CH), UCSC (CA, USA), PSI (CH)
- To be implemented in ETL (CMS) and HGTD (ATLAS)

High electric field enabling the impact ionization of primary charges to achieve fast (→ *better timing performance*) and radiation-hard (→ *less prone to trapping*) sensors

Main focus: time-tagging of particle tracks in order to mitigate pile-up effects expected in high-luminosity future colliders. A time resolution $\sigma_t < 50$ ps is required to obtain such result with the actual reconstruction algorithms

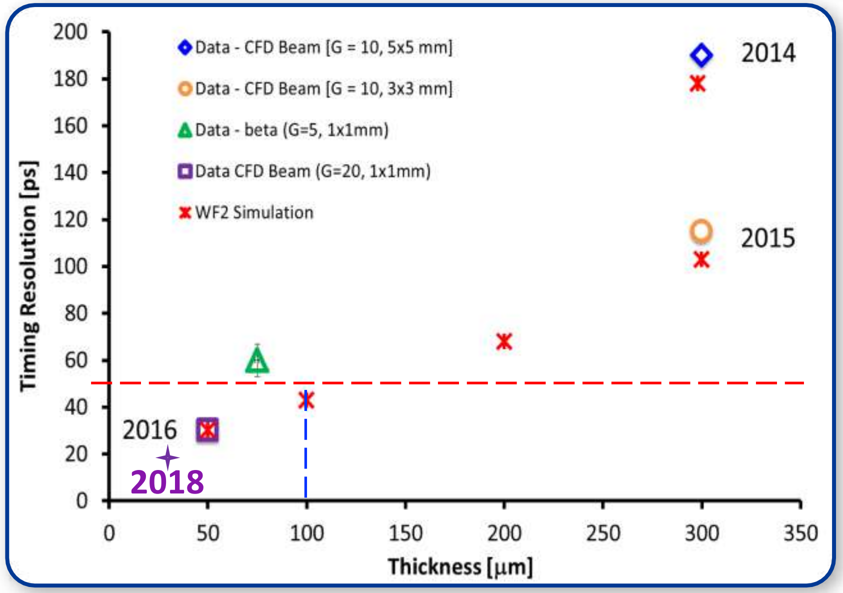


B. State-of-the-art Si Detectors for HE Tracking

3. Novel Structures and Technologies

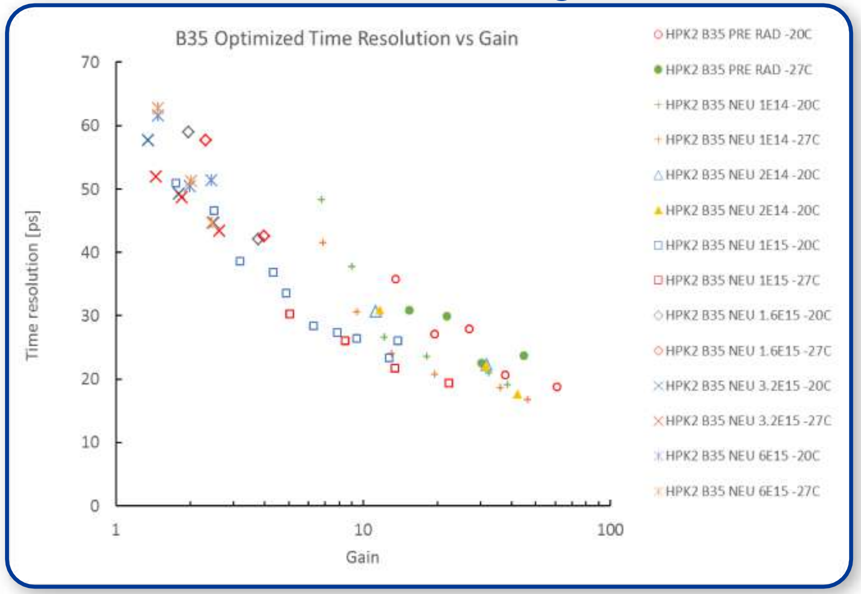
LGAD

σ_t versus LGAD thickness



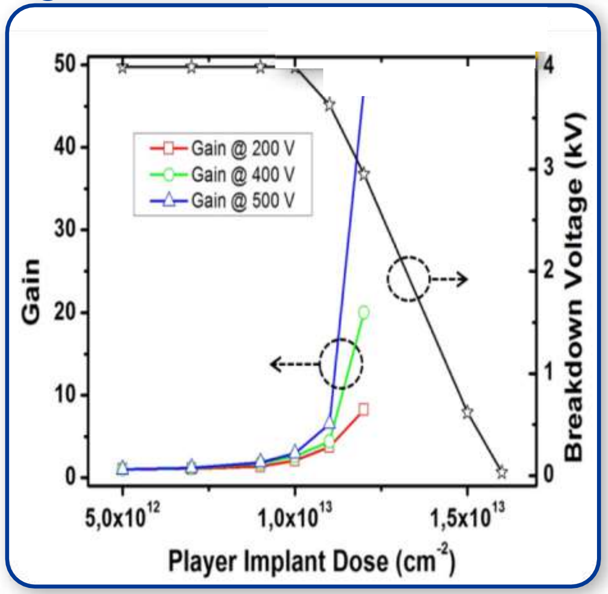
H. F.-W. Sadrozinski, RD50 workshop, Jun 2018

σ_t versus LGAD gain



H. F.-W. Sadrozinski, RD50 workshop, Jun 2018

gain & V_{BD} vs. Boron dose



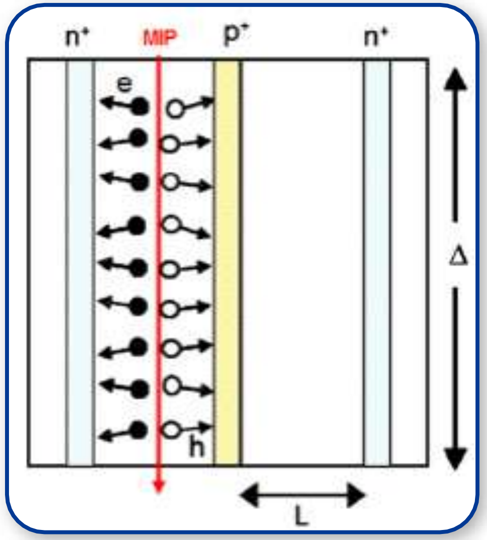
G. Pellegrini *et al.*, NIM-A, (**756**), 12–16, 2014

B. State-of-the-art Si Detectors for HE Tracking

3. Novel Structures and Technologies

3D sensors

- Proposed by S. Parker and C. Kennedy in 1995
- Development mainly focused on innermost pixel layers
- Intensive studies by ATLAS experiment (especially for the IBL) plus several joint MPW productions also with CMS and LHCb
- Two main producers: FBK and CNM



Main detectors Figure of Merit:

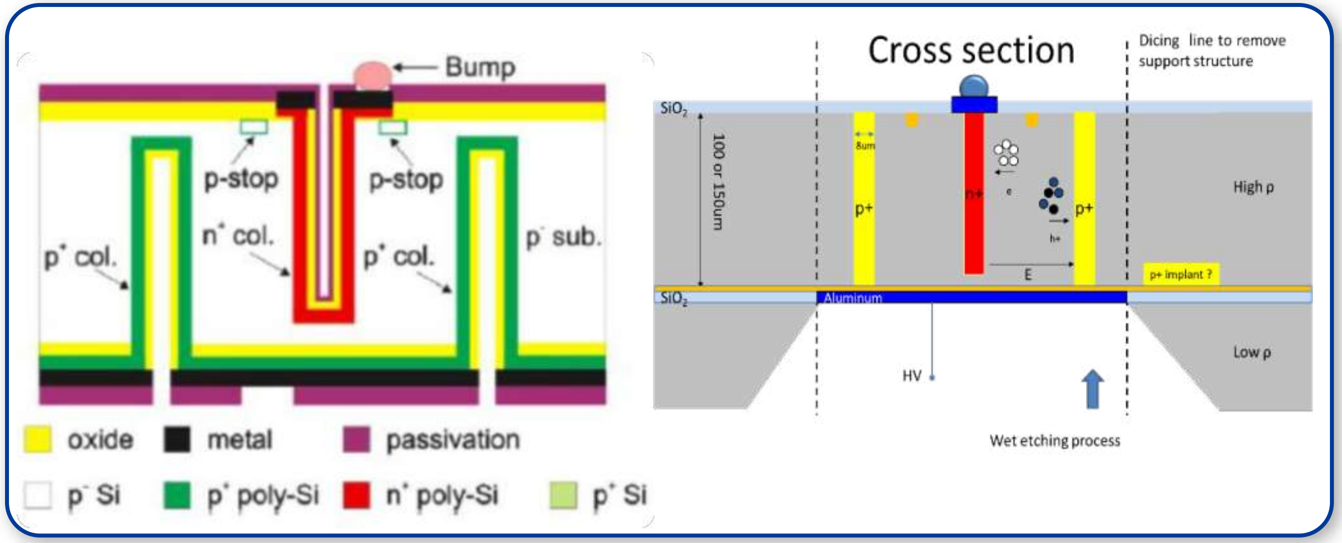
- low depletion voltage (→ *low power dissipation*)
- charge drift decoupled from particle track (→ *short collection time*)
- low drift path (→ *reduced trapping*)
- reduced charge sharing

B. State-of-the-art Si Detectors for HE Tracking

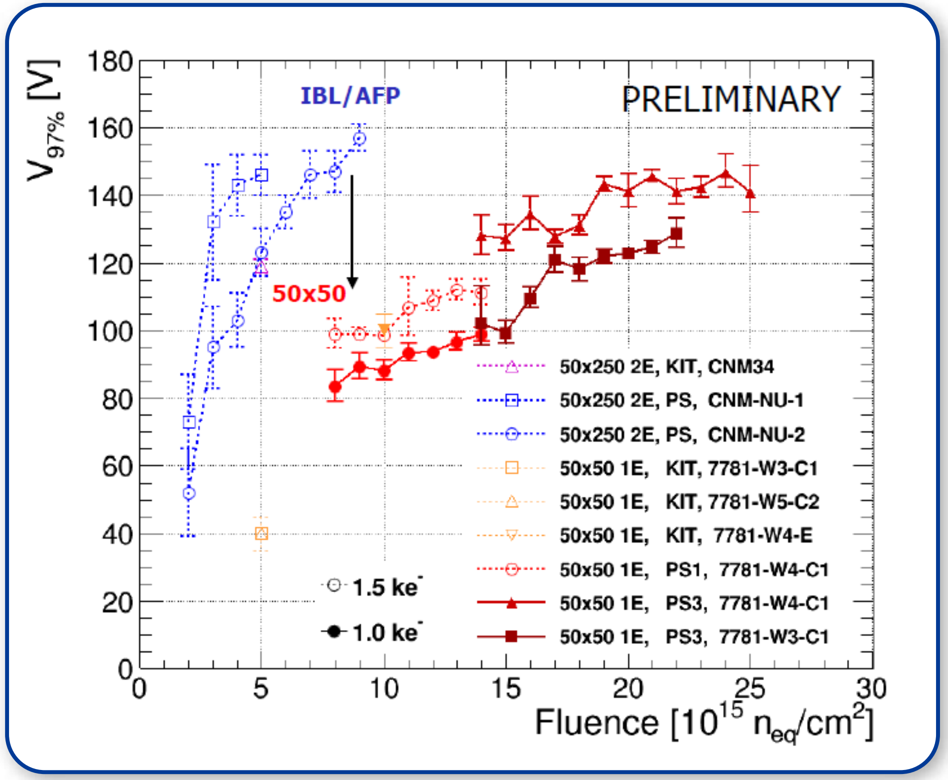
3. Novel Structures and Technologies

3D sensors

- Complicated fabrication: double- or single-sided process
- Efficient even after $3 \cdot 10^{16}$ n_{eq}/cm^2



3D $V_{97\%}$ versus fluence



J. Lange, RD50 workshop, Nov 2017

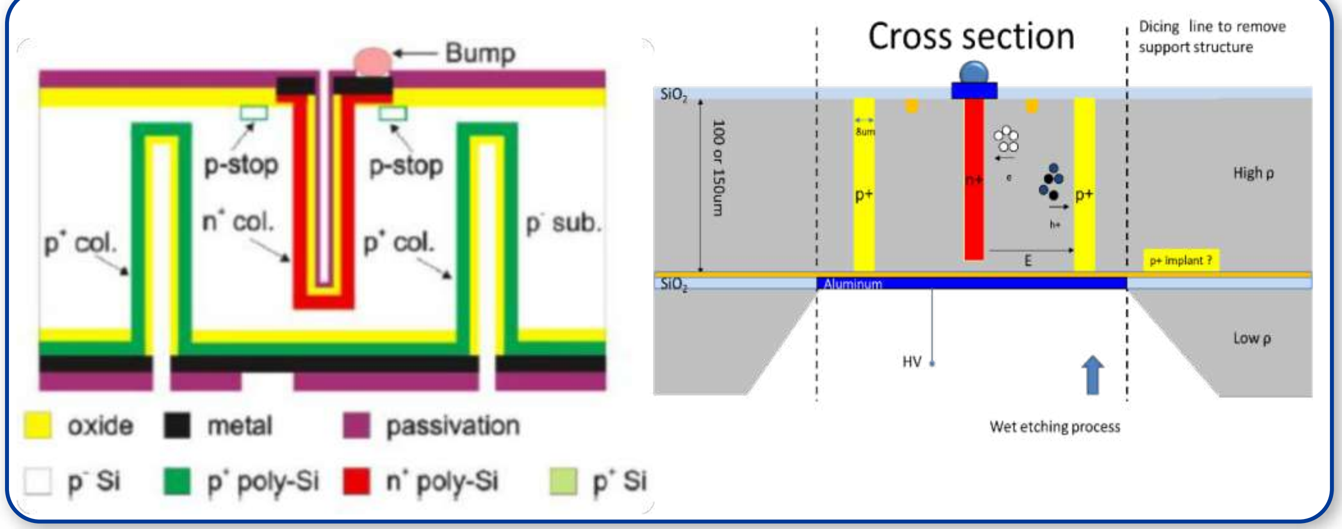
B. State-of-the-art Si Detectors for HE Tracking

3. Novel Structures and Technologies

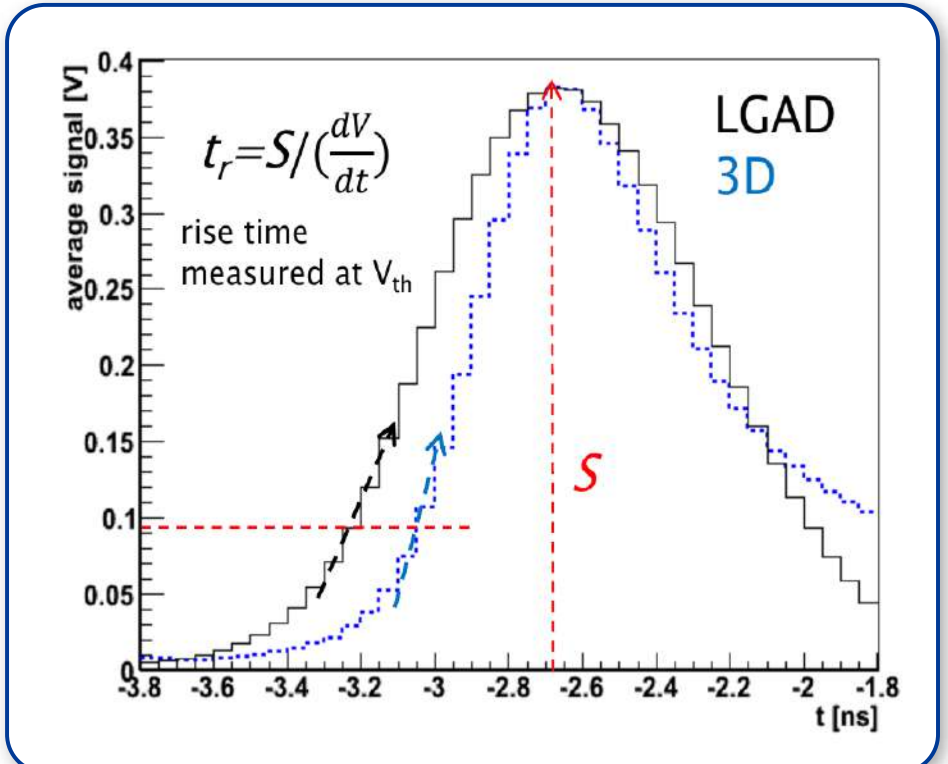
3D sensors

- Complicated fabrication: double- or single-sided process
- Efficient even after $3 \cdot 10^{16}\ n_{eq}/cm^2$
- Very good timing performances: $\sigma_t \sim 30$ ps* ($V > 100$ V, $T = -20$°C)

*see G. Kramberger presentation at TREDI workshop 2019



3D / LGAD signals



G. Kramberger, RD50 workshop, Nov 2018

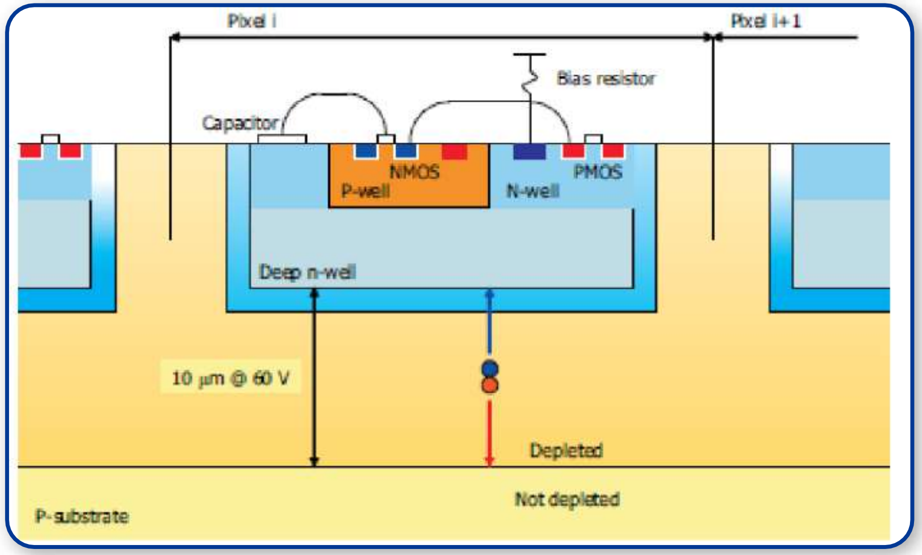
B. State-of-the-art Si Detectors for HE Tracking

3. Novel Structures and Technologies

HV-CMOS

Main detectors Figure of Merit:

- Depleted active pixel detectors implemented in CMOS process
- Sensor element is deep *n*-well in (usually) low resistivity (~10 Ωcm) *p*-type substrate
- The main charge collection mechanism is drift in a very thin depletion region 10-20 μm. Substrate can be furtherly thinned down
- Depletion at ~60 V with ~10 μm leads to charge collection of ~1000 electrons
- Both pixels and strips geometries are allowed
- AC-coupling to the chip is possible

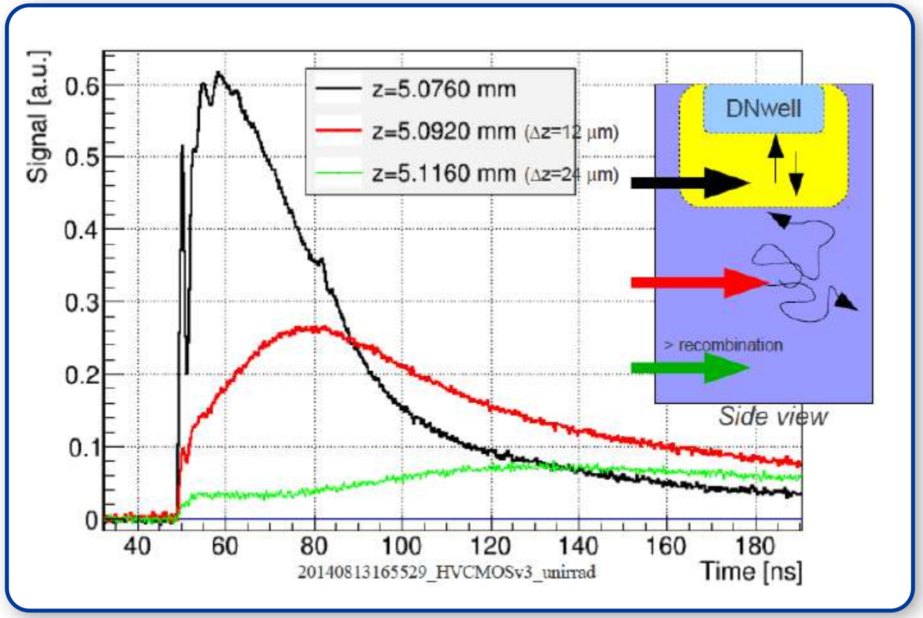


3. Novel Structures and Technologies

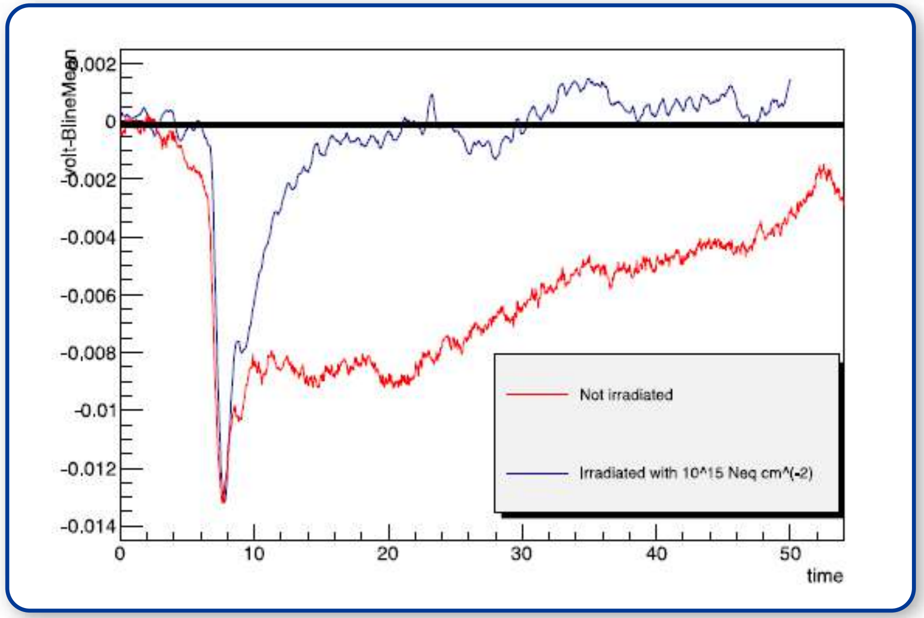
HV-CMOS

- characterization with edge-TCT: induce a current across the thickness using a collimated IR pulsed laser
- drift and diffusion signal components visible. Diffusion partly disappearing with irradiation (due to trapping)

M. Fernandez, RD50 workshop, Nov 2014



M. Fernandez, VERTEX, 2014



B. State-of-the-art Si Detectors for HE Tracking

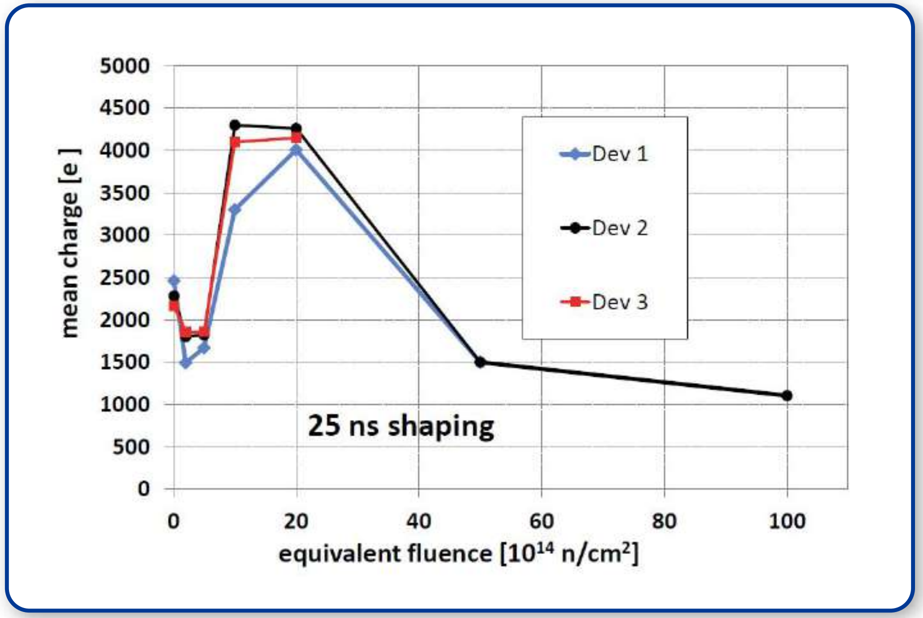
3. Novel Structures and Technologies

HV-CMOS

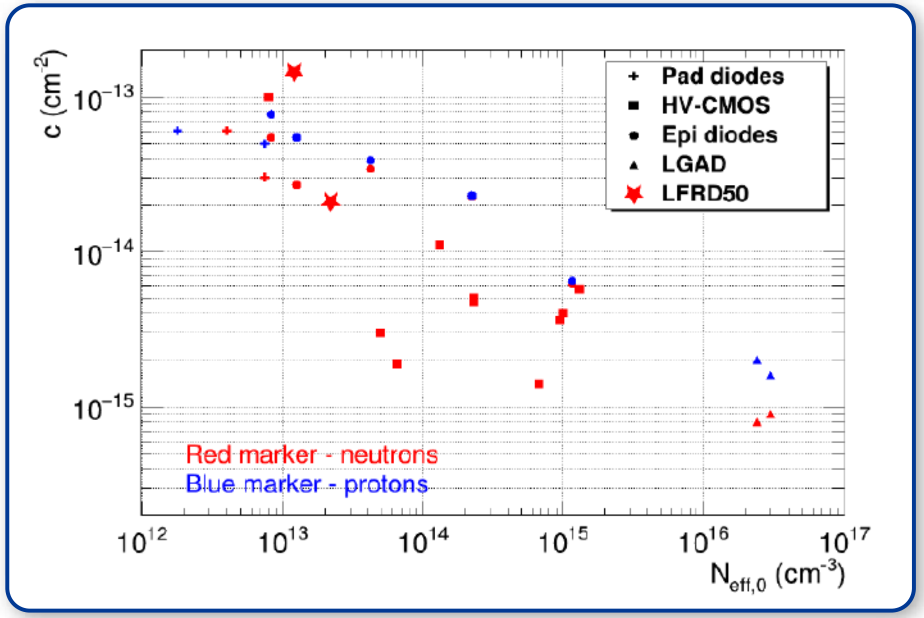
- CCE rising above initial value for fluences in order of some 10^{15} n_{eq}/cm^2
- almost comparable acceptor de-activation for LGAD and CMOS

$N_A(\phi) \approx N_A(0) \cdot \exp[-c \cdot \phi]$

A. Affolder *et al.*, JINST, **11**, P04007



I. Mandic, RD50 workshop, Nov 2018

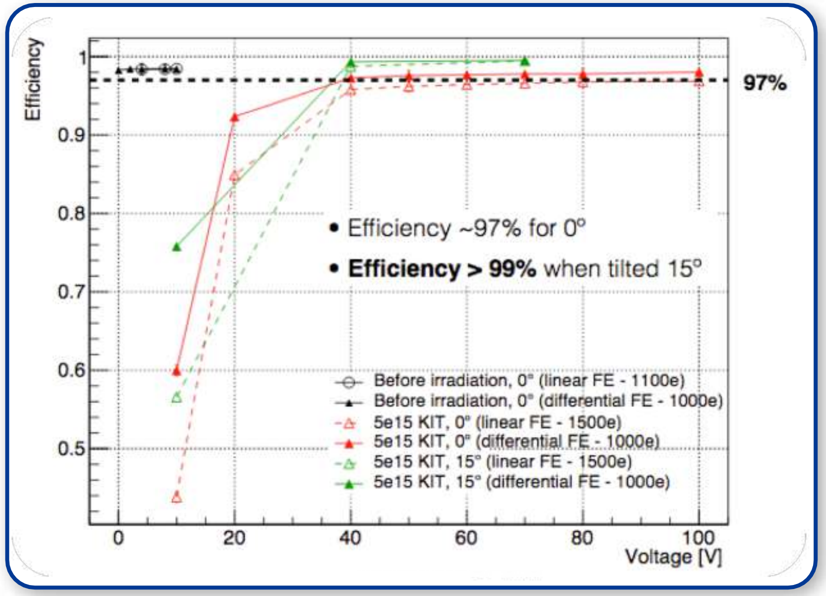


B. State-of-the-art Si Detectors for HE Tracking

3. Novel Structures and Technologies

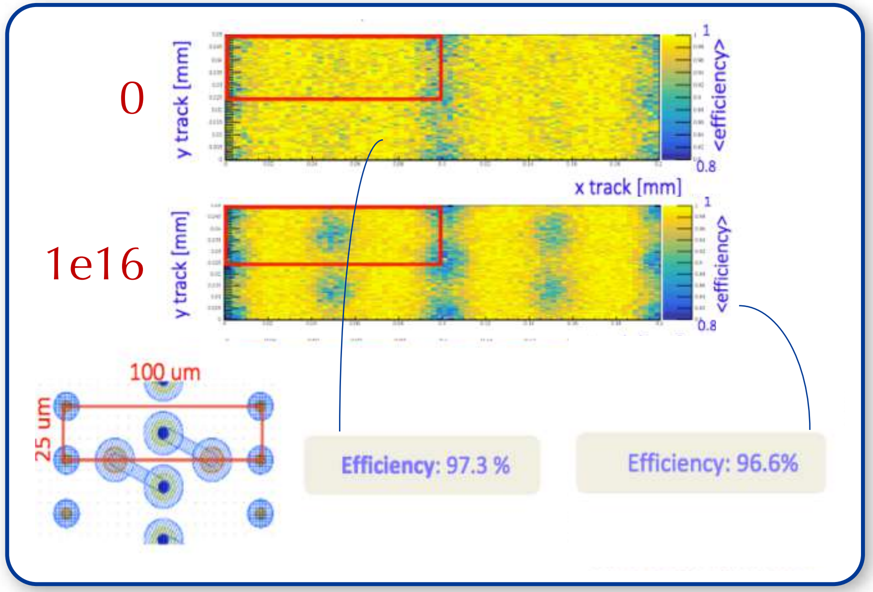
Full-detector systems (RD53A+3D chip prototype for HL-LHC): test-beam at CERN SPS

Efficiency versus bias



G. Giannini, RD50 workshop, Nov 2018

Efficiency maps @ 0°



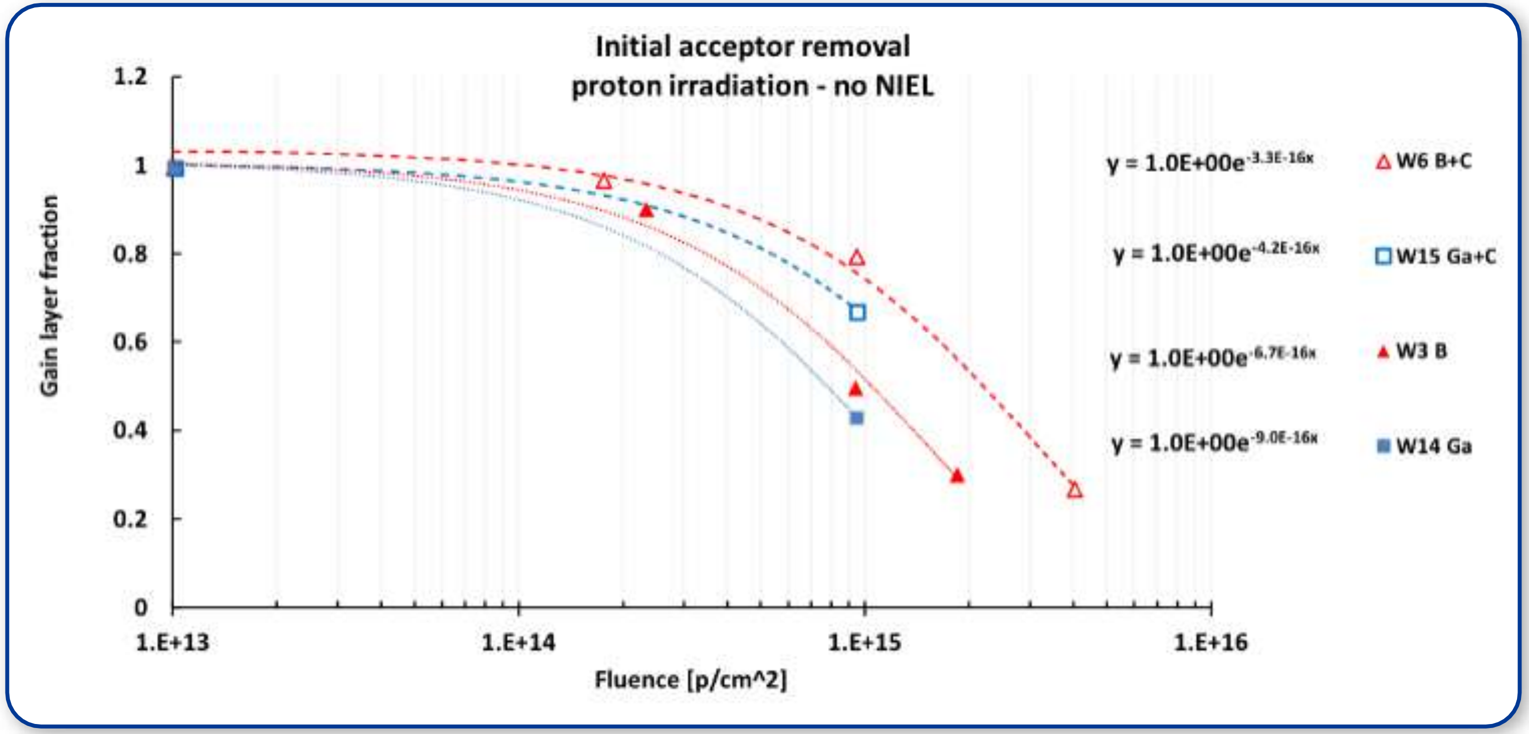
G. Alonso, RD50 workshop, Nov 2018

B. State-of-the-art Si Detectors for HE Tracking

3. Novel Structures and Technologies

Radiation-hardness studies: changes of the *p*-type gain layer in LGAD by FBK

M. Ferrero *et al.*, NIM A, **919**, 16-26, 2017

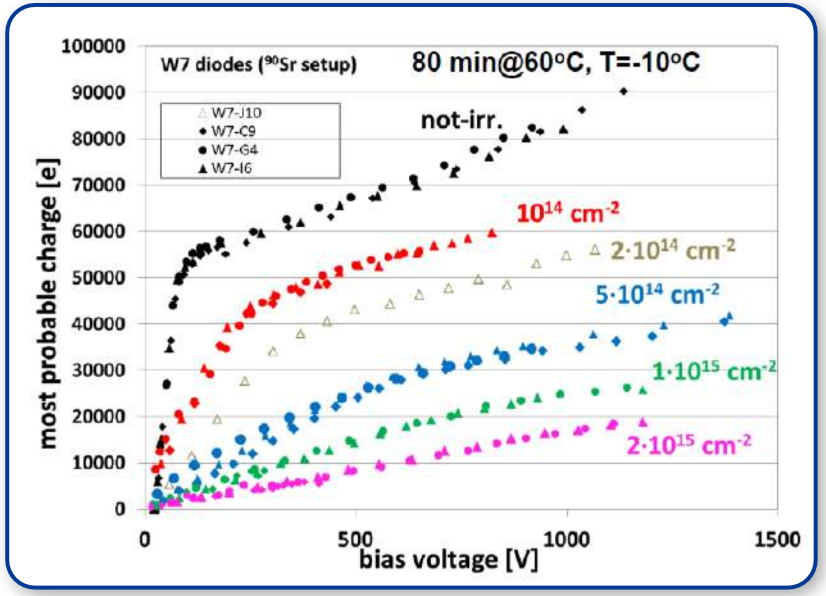


B. State-of-the-art Si Detectors for HE Tracking

3. Novel Structures and Technologies

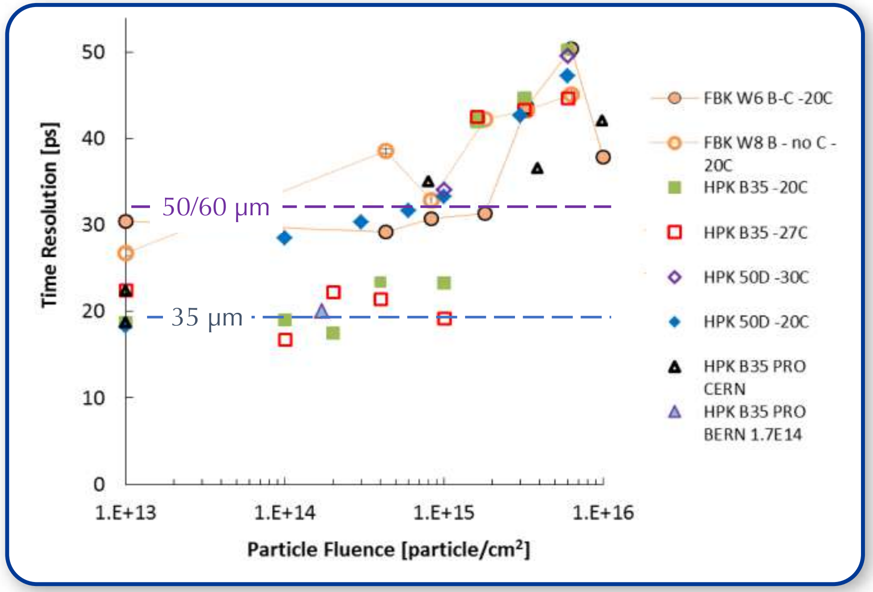
Radiation-hardness studies

LGAD collected charge versus bias



G. Kramberger, RD50 workshop, Jun 2014

LGAD σ_t versus fluence



H. F.-W. Sadrozinski, RD50 workshop, Jun 2018

B. State-of-the-art Si Detectors for HE Tracking

3. Novel Structures and Technologies

Timing performances and 4D-tracking: fill-factor improvements in LGAD

- Combine the high spatial resolution of segmented silicon sensors with avalanche multiplication for producing high S/N devices

$$\sigma_t^2 = \sigma^2_{\mathrm{TimeWalk}} + \sigma^2_{\mathrm{Landau}} + \sigma^2_{\mathrm{distorsion}} + \sigma^2_{\mathrm{jitter}} + \sigma^2_{\mathrm{TDC}}$$

$$\sigma^2_{\mathrm{TimeWalk}} = \left[\frac{V_{\mathrm{th}}}{S/t_{\mathrm{rise}}}\right]_{\mathrm{RMS}} \propto \left[\frac{N}{\mathrm{d}V/\mathrm{d}t}\right]_{\mathrm{RMS}}$$

$$\sigma^2_{\mathrm{jitter}} = \frac{N}{\mathrm{d}V/\mathrm{d}t} \approx \frac{t_{\mathrm{rise}}}{S/N}$$

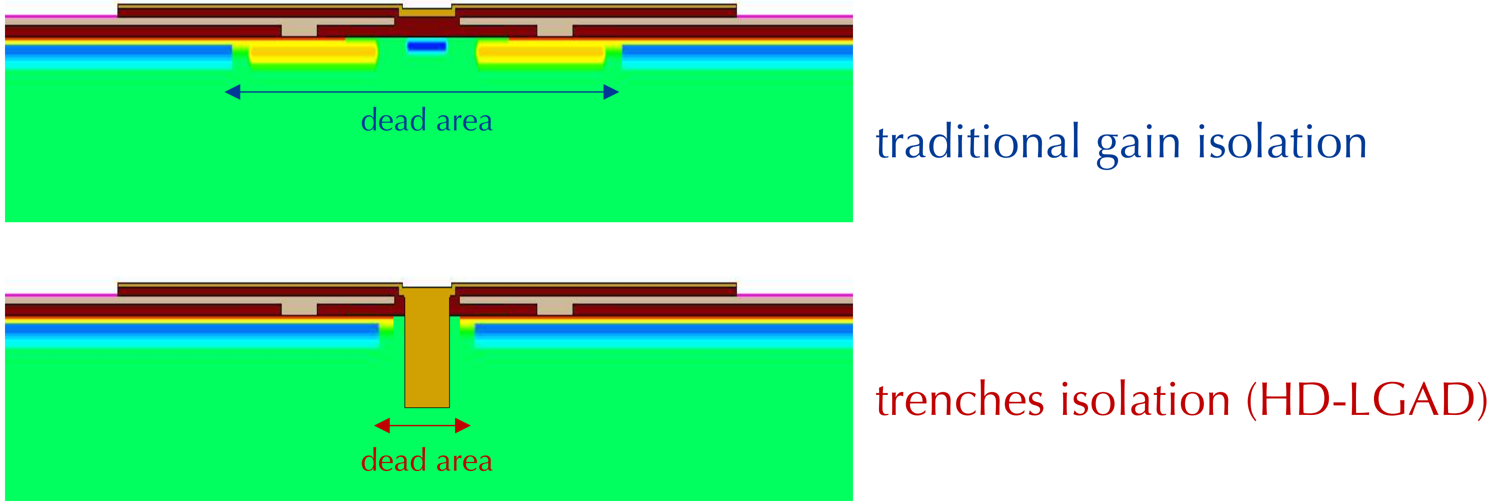
- Maximize the signal slope dV/dt → large and fast signals
- Signal S increasing with gain G → expected jitter: ~1/G
- Minimize the noise N

B. State-of-the-art Si Detectors for HE Tracking

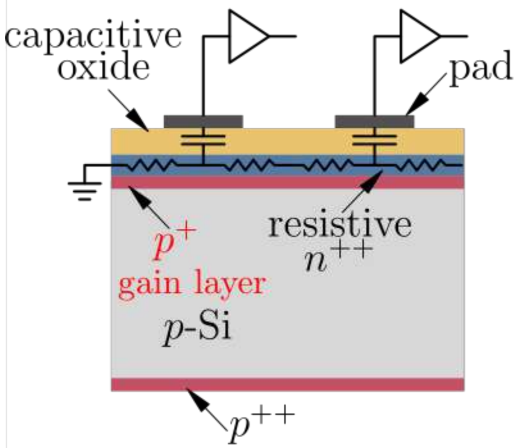
3. Novel Structures and Technologies

Timing performances and 4D-tracking: fill-factor improvements in LGAD

- To have a good timing reconstruction the signal must be homogeneous, i.e. without any losses
- A pixel-border termination region is necessary to host all the structures controlling the electric field



AC-LGAD / RSD projects



Presentation Outline

A. The RD50 Collaboration

B. State-of-the-art Silicon Detectors for High-Energy Particle Tracking
   1. Radiation Damage and Defects Characterization
   2. Detectors Characterization
   3. Novel Structures and Technologies

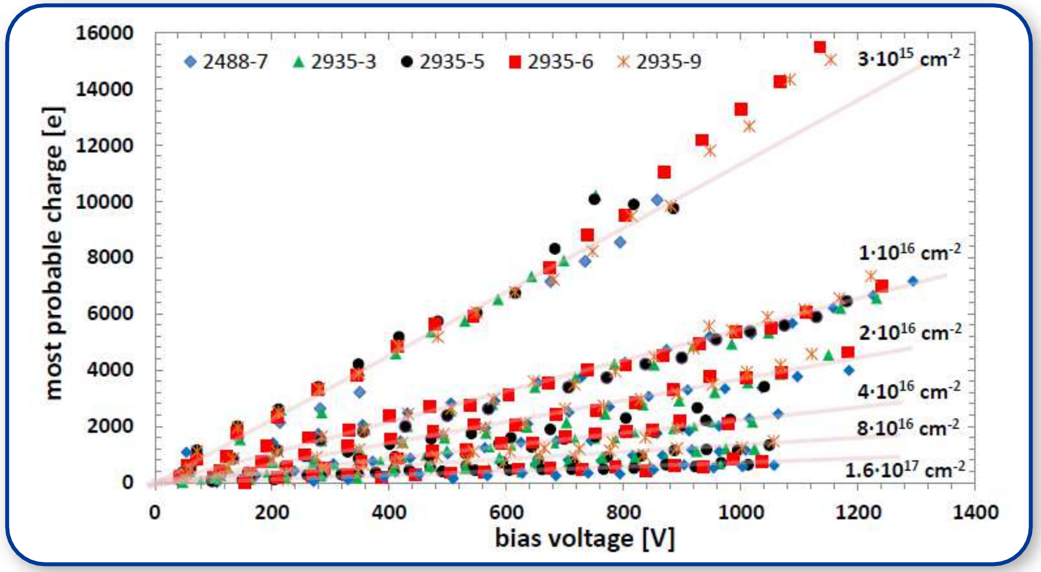
C. Radiation Tolerance also Beyond HL-LHC

C. Radiation Tolerance also Beyond HL-LHC

Exploring final limit: > 10^{17} n_{eq}/cm^2. Still alive?

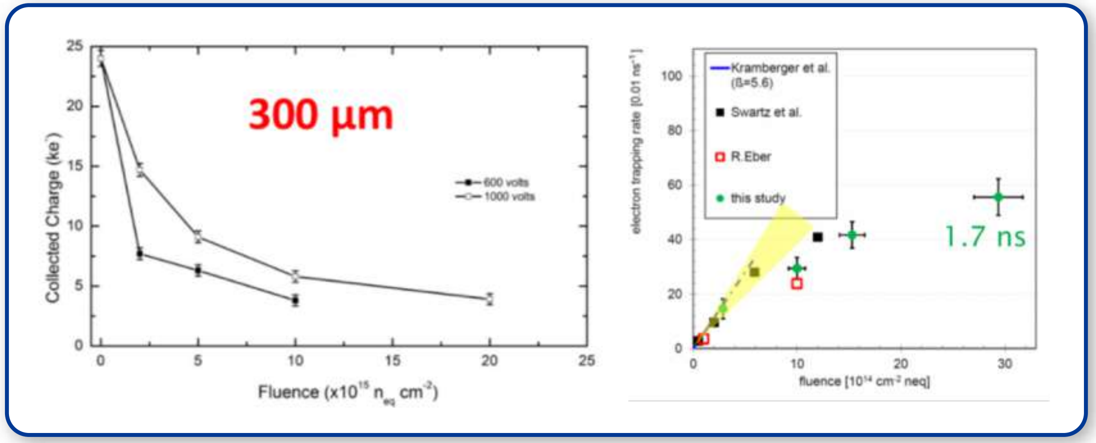
► Increase of trapping with irradiation but, at ultra-high fluences, the trap production saturates …

CC with fluence



M. Mikuz, 28th RD50 workshop, Jun 2016

charge trapping with fluence



W. Adam *et al.*, JINST, **11**, P04023, 2016 & S. Wonsak, RD50 workshop, Dec 2015

C. Radiation Tolerance also Beyond HL-LHC

Exploring final limit: > 10^{17} n_{eq}/cm^2. Still alive?

- Increase of trapping with irradiation but, at ultra-high fluences, the trap production saturates …
- To get rid of such bulk effects, one should exploit reduced active volumes, that generate small signals. Possible solutions:
  - Use the internal gain → thin-LGAD (timing)
  - Decouple drift path and total charge deposition → 3D sensors (general tracking purposes)
- Radiation up to $7 \cdot 10^{17}$ n_{eq}/cm^2 (FCC) still remains challenging. Need for material/detectors characterization and modeling
- Besides the radiation-tolerance requirements, also spatial and timing resolution, as well as power consumption, are requiring even more demanding performances

Summary

- **RD50** is a CERN R&D transversal collaboration. Common **projects** with **experiments**: **irradiation** campaigns, **test-beams**, **wafer** procurement and common **sensor** development. **Silicon** experts from different experiments meet together and discuss/share information
- Most of the activity is focused on Si, in particular **radiation hardness** towards **HL-LHC** and beyond
- Topics covered:
  - **Defect** characterization in Si
  - **Detector** characterization
  - Development of **new characterization techniques**
  - Development of **novel structures** and **full detector systems** for **space/time particle tracking**
- Goal: provide **radiation-hard detectors** for future **High-Energy Physics** experiments

Thanks for your attention!